

MICROSCOPIC VOID DETECTION AS A PRELUDE TO PREDICTING REMAINING LIFE IN ELECTRIC CABLE INSULATION

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ABSTRACT

A reliable method of testing for remaining life in electric cable insulation has continued to elude the nuclear industry as it seeks to extend the life and license of its nuclear stations. Until recently, a trendable, measurable electrical property has not been found and unexpected cable failures continue to be reported. Most reliable approaches to date rely on monitoring mechanical properties, which are assumed to degrade faster than the insulation's electrical properties. This paper will introduce a promising technique based on void characterization, which is truly dependent on an electrical property related to dielectric strength. A relationship between insulation void characteristics (size and density) and the onset of partial discharge is known to exist. A similar relationship can be shown between void characteristics and unacceptable leakage currents (another typical cable failure criterion).

This paper will report on research proving the existence of trendable void characteristics in commonly used electric insulation materials and techniques for detecting the voids (both laboratory and field based techniques). Acoustical microscopy was found to be promising for non-destructive *in situ* detection and monitoring of void characteristics in jacketed multi-conductor insulation while ignoring the jacket. Future papers will report on correlating void growth rate with environmental factors.

1. INTRODUCTION

No new nuclear power plants have been ordered in the US since 1979 and many have been shutdown permanently. In order to continue to meet the growing energy needs of the US, it will be necessary to extend the term of the operating license of many if not all of the remaining plants. The framework of such a license term extension is established in 10 CFR Part 54 - the License Renewal Rule. An essential part of this process is a demonstration that the effects of aging can be managed to the extent that equipment functions are maintained. Electric cable has been identified to be a key part of this demonstration and the regulator has, in general, been unwilling to accept analysis alone to support license renewal. Therefore, an economical form of testing in lieu of full-scale cable replacement is sought by the industry.

In general, testing of cable insulation has been limited to monitoring and trending of mechanical properties (such as loss of elongation retention and hardness) and forms of electrical testing that are go/no go results oriented, (such as insulation resistance,

polarization index, and time domain reflectometry). These techniques have not provided useful and trendable remaining life information.

1.1 Purpose of Research

A multi-phase research project has been initiated to assess the value of being able to characterize electrical insulation void information and correlate it to remaining useful life. This paper will report on the first phase, which had the objectives of:

1. Confirming that micron-size voids exist and can be found in commonly used solid dielectric insulation if viewed with sufficient level of magnification. (This objective was important because it establishes a foundation for future research efforts.)
2. Investigating and evaluating the feasibility of microscopy technology that can detect and measure a micron-size void inside a conductor insulation material. This project placed precedence on a technique that is nondestructive in nature.

Subsequent papers will report on the correlations between insulation aging rates and changes in void characteristics from exposure to environmental factors. This information can then be used to predict the remaining life of the insulation.

1.2 Why Voids?

Manufacturing processes of cable can cause cavities to appear within the insulation. It has long been recognized that large sized cavities or voids can lead to immediate or short-term cable failure. Gases within the voids ionize much more easily than the surrounding solid dielectric when subject to an imposed potential. If the voids are large or numerous enough, a partial discharge path (called treeing) can occur between the applied potential. For this reason, manufacturers have been responsible for testing their cable to assure no voids of significant size exist prior to release from the factory.

More recently Namiki *et al* (1980), Laurent and Mayoux (1992), Mammeri *et al* (1995), and others have evaluated the significance of extremely small voids in insulation systems. However, none have comprehensively evaluated techniques for detecting micron size voids nor attempted to correlate aging induced void density increase or void growth rates to remaining useful life.

There is a direct correlation between existence of voids and the potential that causes dielectric breakdown or cable failure. Research to date suggests that as electrical insulation ages the polymer molecules breakdown from exposure to heat and radiation. This breakdown releases gaseous molecules, which cause void size and density to increase. Rates of breakdown and void size and density increase rates are related to rates of exposure to environmental and operational stressors. The increase in the size and density of voids, in effect reduces the equivalent insulation thickness between adjacent conductors subject to a nonzero potential.

It can also be shown that the existence of voids in insulation increases the energy storage ability of the electric field created between adjacent, differently energized conductors. Therefore, the size and density of voids affects the capacitance of the dielectric and, therefore, leakage current when the conductors are subject to different

time varying electric potentials. High void content causes high equivalent capacitive effects, which can lead to excessive leakage current - a primary failure criterion for instrument and most control cables.

As a result, it is relevant that this paper report on research into ways to detect, image, and monitor void characteristics as a prelude to estimating remaining life of electric insulation.

2. SAMPLE DESCRIPTION

Eight naturally aged cable insulation samples were obtained from a nearby power plant and unaged samples were obtained from a cable manufacturer. Three of the eight samples (1, 3, and 8) were subjected to multiple method image testing and are summarized in Table 1. Table 1 also includes Sample 5, because of its use *in situ* configuration testing as described below, and Sample 6 to show an example of a pre-aged void characteristic.

Table 1 Cable Sample Information.

<i>Sample Number</i>	<i>Insulation Type</i>	<i>Insulation Thickness</i>	<i>Manufacturer</i>	<i>Size</i>	<i>Voltage Rating</i>	<i>Comments</i>
1	XLPE (polyethylene)	280 mils	Essex	750 MCM	28 kV	Naturally aged 23 years
3	XLPE (polyethylene)	185 mils	Essex	1/0 AWG	15 kV	Naturally aged 19 years
5	EPR (ethylene propylene rubber)	75 mils	Okonite	2/0 AWG	600 V	Unknown amount of aging
6	XHHW-2 (polyethylene)	50 mils	Rockbestos	3/c-1/0 AWG	600 V	Unaged, jacketed
8	EPR (ethylene propylene rubber)	60 mils	Rockbestos	1/0 AWG	600 V	Unaged

3. METHODS OF IMAGE TESTING

Four types of image testing were attempted: conventional ultrasound (200 kHz to 10 Mhz), acoustic microscopy (10 MHz to 1 GHz), optical microscope, and scanning electron microscope (SEM).

Three conventional ultrasound vendors were contacted for assistance because it is well known that conventional ultrasound is used quite reliably for detecting flaws (voids) in metal piping and vessels. However, based on contacts with these vendors, such approaches were found to be limited in usefulness for imaging the interior of polymers such as electrical insulation. The 10 MHz upper operating frequency limit prevents useful resolution of voids below 50 to 100 micrometers. It was also found that polymers exhibit higher attenuation of ultrasound wave properties as compared to metallic materials. Only sound waves of at least 10 MHz have sufficient energy to penetrate the electric cable's outer jacket.

Improved results were obtained with acoustic microscopy. Sound waves reflect at interfaces of material density decreases such as from solid polymer to a gaseous void site. The sharper the discontinuity in density, the stronger the reflected wave. Sonoscan, Inc. volunteered use of its C-Mode Scanning Acoustic Microscope (C-SAM) Series D6000 for this research. This C-SAM operates at 10 to 100 MHz, which was found to provide the desired resolution. The C-SAM through adjustment of the observed time interval of the reflected wave was found to be capable of filtering out reflections from the cable's jacket material. Therefore, images of the electric insulation's internal void characteristics were readily apparent. Figures 1 and 2 provide two sample views of electric insulation using acoustic microscopy. Figure 1 is a view of a jacketed cable as it would appear if monitored in the field (in situ). Figure 2 is a prepared (cut) sample view.

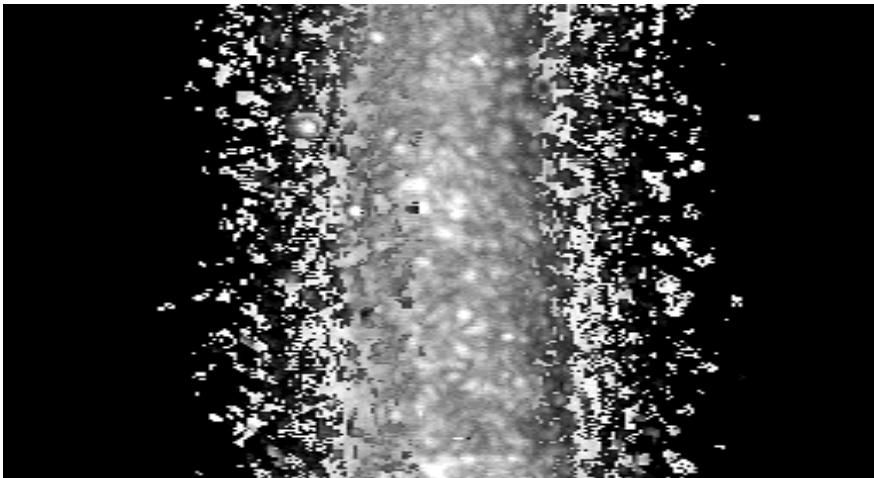


Fig. 1 Sample 5 (Aged Ethylene Propylene) Viewed with C SAM at 15 MHz

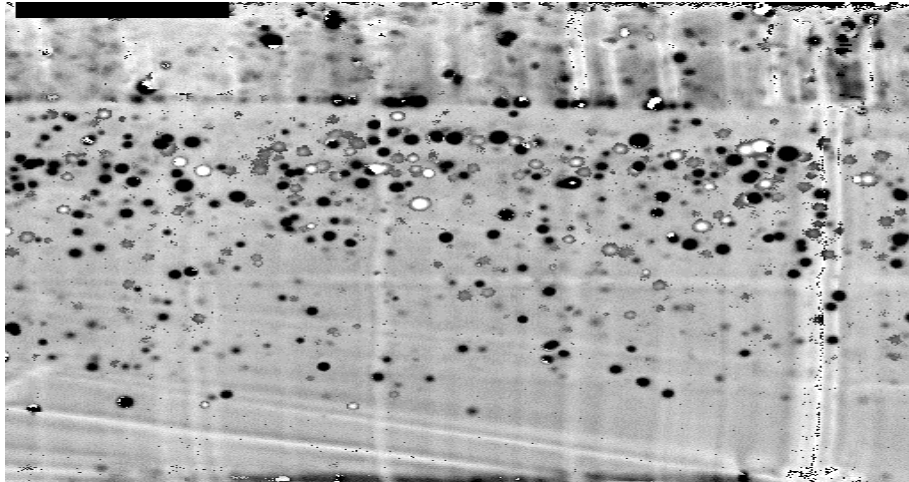


Fig. 2 Sample 3 (Aged Polyethylene) Viewed with C SAM at 50 MHz

The optical and scanning electron microscope facilities at the University of Michigan, Ann Arbor were used to further explore void characterizations in electric insulation. The optical microscope used was an Olympus Model PME-33 Inverted Metallurgical microscope with the magnification optimally set at 500. Figure 3 is a sample optical view.

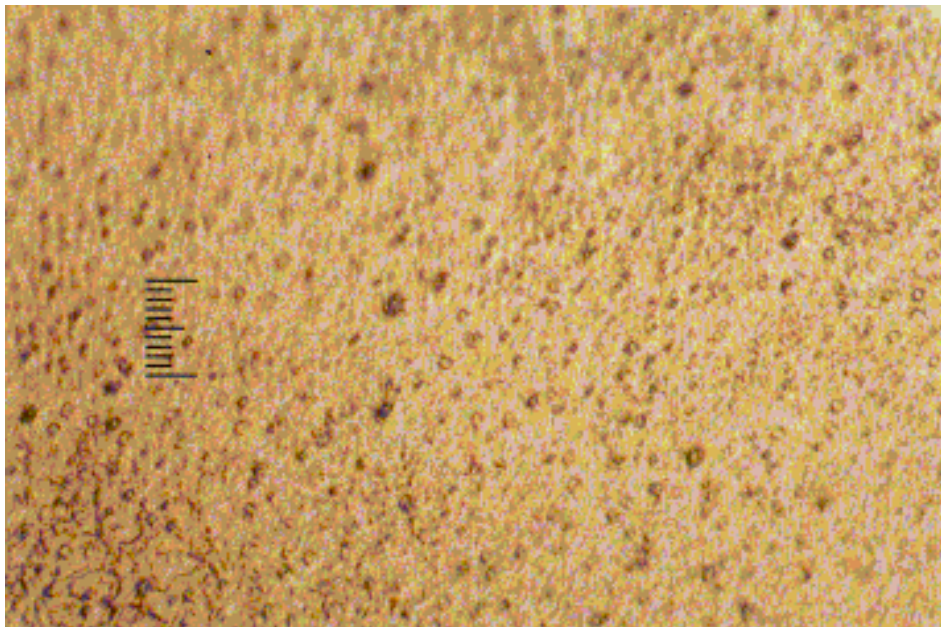


Fig. 3 Sample 1 (aged polyethylene) using an optical microscope at 500X

The SEM used was a Hitachi S-800 with magnification capability of 1,000 to 20,000. It was found that the SEM was particularly useful for searching for voids in new insulation material where the voids were found to be of relatively small size (0.3 to 12 microns). Figures 4 and 5 are examples of SEM Views.

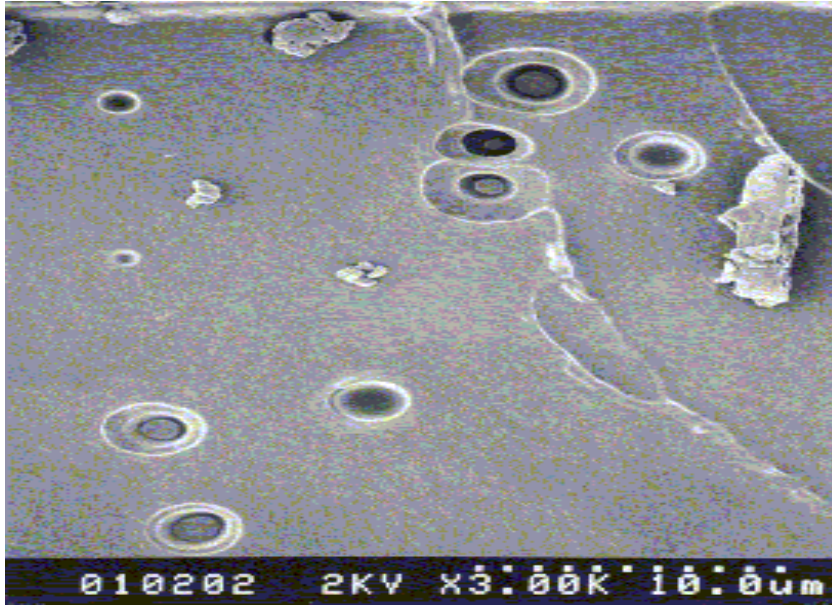


Fig. 4 Sample 1 (aged polyethylene) using an SEM at 3000X

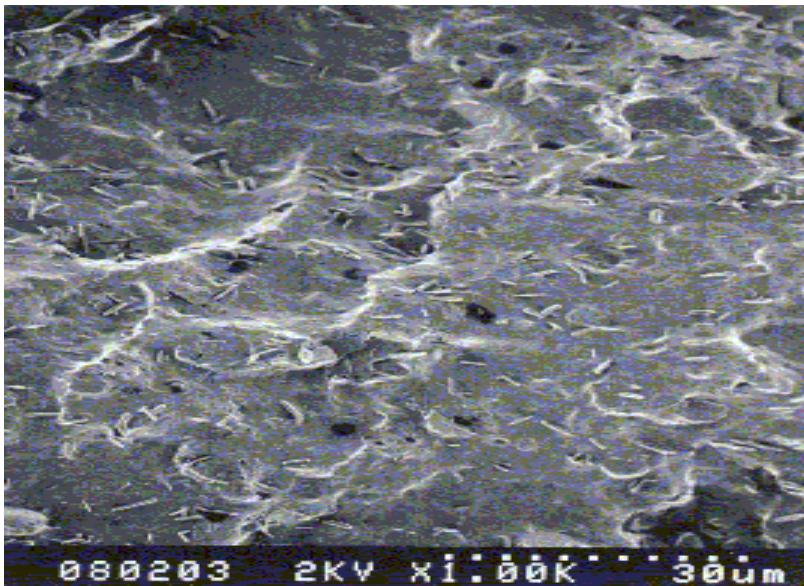


Fig. 5 Sample 8 (new EPR) using an SEM at 2000X

4. RESULTS

Table 2 below summarizes void parameters for the samples listed on Table 1. Additional related and supportive information can be found in Avila (1995) and at <http://www.adventengineering.com/service/research/research.htm>.

Table 2 Results of microscopy examination.

<i>Sample Number</i>	<i>Sample Description</i>	<i>Average Void Size (in microns)</i>	<i>Void Density (in voids/cm³)</i>	<i>Testing Method</i>
1	Aged PE	7	500	Optical 200X
1	Aged PE	6	500	Optical 500X
1	Aged PE	3	300	SEM 3000X
3	Aged PE	<75	>140	C SAM
3	Aged PE	12	225	Optical 200X
3	Aged PE	5	250	Optical 500X
5	Aged PE	Not measured	Not measured	C SAM
6	New PE	0.4	3000	SEM 12000X
8	New EPR	10	100	Optical 200X
8	New EPR	4	700	SEM 1000X
8	New EPR	2	1000	SEM 2000X

Note: Void size and density for the C SAM readings could not be accurately established because magnification information was not available or correlatable. In the future, calibration can be accomplished based on prior optical or SEM microscope readings.

5. CONCLUSIONS

Conventional ultrasound approaches were found to not be effective for detecting voids of 1 to 10 microns in size in polymers. However, acoustic microscopy (a more advanced form of ultrasound using frequencies above 10 MHz) was found to be more viable. Acoustical microscopy with improved calibration techniques and higher power levels at frequencies above 10 MHz could prove practical for non-destructive testing of cable insulation in the field. Optical and SEM microscopy techniques, although requiring sample preparation in laboratory use, allow ready identification of void characteristics and will, therefore, play an essential role in establishing a data base of void parameters (size and density) and remaining correlations to life for various materials and environmental stressors.

NOMENCLATURE

CFR	US Code of Federal Regulations
C SAM	C-Mode scanning acoustical microscope
kHz	kilohertz
MHz	megahertz
SEM	Scanning Electron Microscope
PE	polyethylene
EPR	ethylene propylene rubber

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